Systematic study of energy-spin entry distributions at the proton dripline in the $A \sim 170$ region*

M.B. Smith[a], J.A Cizewski[a], M.P. Carpenter[b], F.G. Kondev[b], R.V.F. Janssens[b], K. Abu Saleem[b], I. Ahmad[b], H Amro[c], M. Danchev[d], C.N. Davids[b], D J. Hartley[d], A. Heinz[b], T.L. Khoo[b], T. Lauritsen[b], C.J. Lister[b], W.C. Ma[c], G.L Poli[b], J.J. Ressler[b], W. Reviol[e], L.L. Riedinger[d], D. Seweryniak[b] and I. Wiedenhöver[b,†]

[a]Department of Physics and Astronomy, Rutgers University, New Brunswick, NJ 08903 USA

[b]Argonne National Laboratory, Argonne, IL 60439 USA

[c]Department of Physics, Mississippi State University, MS 39762 USA

[d]Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996 USA

[e]Chemistry Department, Washington University, St. Louis, MO 63130 USA

Proton-rich Pt, Au and Hg nuclei have been populated following the bombardment of ^{92,94,96}Mo targets by beams of ^{84}Sr. Comparisons are made between the entry distributions associated with both low- and high-spin $^{173-177}$Au isomers, as well as the more stable Pt and Hg isobars, as a function of neutron number. This is the first time that a systematic study of such distributions has been conducted for nuclei near and beyond the proton dripline.

1. INTRODUCTION

There is considerable current interest in the study of weakly-bound nuclear systems, particularly in the limits of excitation energy and angular momentum that such systems can sustain. Recently, the energy-spin (E, I) phase space of ^{254}No [1] has been determined. These distributions show that this very heavy nucleus, which would be unstable against spontaneous fission but for shell corrections, is surprisingly robust. Nuclei which are unstable to decay by proton emission, either from their ground state or from an isomeric state, provide another laboratory for the study of the amount of energy and angular momentum which a weakly-bound system can withstand. The high-spin population of these nuclei in heavy-ion reactions should also be limited by fission of the compound

system. Since both low- and high-spin isomers have often been identified in the same nucleus, entry distributions leading to yrast and non-yrast excitations can be compared and contrasted. For nuclei close to stability, the entry distribution reflects the number of particles evaporated from the compound system. However, as one moves towards the proton dripline, it is reasonable to expect that the weak binding of the last proton should affect the energy and angular momentum that the nucleus can sustain, when compared to an isobar in which the last proton is more strongly bound. In addition, the barrier for decay is dependent on the orbital angular momentum ℓ of the decaying state. The barrier is considerably higher for emission from a high-ℓ state, than for emission from a state of low ℓ. We might thus expect that entry-distribution effects could be enhanced for low-spin isomers, for which the barrier is lower. In the paper we report on the shapes of the entry distributions that characterise $_{79}$Au nuclei beyond the proton dripline, and compare these distributions to those of more stable $_{78}$Pt and $_{80}$Hg isobars produced under the same experimental conditions.

2. EXPERIMENTAL TECHNIQUE AND ANALYSIS

High-spin states in the isotopes of interest were populated following the bombardment of ^{92,94,96}Mo targets by beams of ^{84}Sr, provided by the ATLAS accelerator facility at Argonne National Laboratory. Recoiling fusion-evaporation products were identified using the Argonne fragment mass analyser [2] and the recoil-decay tagging method [3,4] was used to select the α-decaying isomers of interest. Isotopic identification was performed through measurements of the mass-to-charge ratio M/Q, in a parallel-grid avalanche counter (PGAC), and through correlation, within a time interval of approximately three half-lives, of an alpha-decay of interest with an implant in the same pixel of a double-sided Si strip detector (DSSD). Prompt γ-rays were detected using the GAMMASPHERE Ge detector array [5], with no heavimet collimators in place on the BGO suppression shields. The array consisted of 101 suppressed Ge detectors, with a further five BGO shields in position, in order to cover a solid angle as close to 4π as possible. Total modular energy H and modular multiplicity K were measured, where a module consists of a Ge detector plus its BGO shield (or the shield alone for the five array positions without Ge detectors).

The known sum-energy and multiplicity response functions of GAMMASPHERE enable the conversion of modular (H, K) into energy E and multiplicity M. The response functions were determined from source measurements, using an event-mixing technique [6]. Based on the response functions, a two-dimensional Monte Carlo unfolding procedure [7,8] can be used to transform the (H, K) distribution into a spectrum of multiplicity versus excitation energy. The dependence of efficiency on multiplicity is taken into account, in order to correct for the effect of trigger conditions.

The multiplicity can be related to angular momentum I by realistic assumptions [1] of the angular momenta carried by the components of the γ-ray cascade. The initial spin of the evaporation residue is deduced using the expression

$$I = \Delta I (M - N_{stat}) + \Delta I_{stat} N_{stat} \tag{1}$$

where ΔI is the average spin removed per photon and N_{stat} is the number of statistical γ-rays emitted. In this work, the following values were adopted: $\Delta I = 2$, $\Delta I_{stat} = 0.25$ and $N_{stat} = 3$, appropriate for a deformed nucleus at moderate spin and excitation energy.

3. RESULTS AND DISCUSSION

Entry distributions have been measured for several isotopes of Pt, Au and Hg with mass A in the region $173 \leq A \leq 177$; for the Hg nuclei, it has only been possible to extract spectra for ^{177}Hg. Figure 1 shows examples of preliminary two-dimensional (E, I) distributions for the isobars ^{175}Au and ^{175}Pt. The yrast lines for these nuclei, obtained from the analysis of discrete γ-ray transitions [9], are also shown.

Projections of the two-dimensional (H, K) spectra are shown in figure 2 for the odd-A cases, normalised to the ^{177}Au data. For ^{173}Au [10] and ^{177}Au [11] two α-decays, from states of opposite parity (π), are observed, and the entry distribution associated with each has been determined. These ground (g) and excited metastable (m) states have the following spin assignments and Nilsson configurations:

$$^{173g}\text{Au}, \ I^{\pi} = \tfrac{1}{2}^{+}, \quad 1/2^{+}[400]; \qquad\qquad ^{173m}\text{Au}, \ I^{\pi} = \tfrac{11}{2}^{-}, \ 11/2^{-}[505];$$
$$^{177g}\text{Au}, \ I^{\pi} = \left(\tfrac{5}{2}^{+}\right), \quad 1/2^{+}[400] \text{ or } 3/2^{+}[402]; \qquad ^{177m}\text{Au}, \ I^{\pi} = \tfrac{11}{2}^{-}, \ 11/2^{-}[505].$$

For both isotopes, the spectra shown in figure 2 are correlated with the decay of the $\tfrac{11}{2}^{-}$ isomer. Table 1 summarises the average modular energy $\bar{H}$ and average modular multiplicity $\bar{K}$, along with their full-width half-maxima δH and δK, associated with each α-decay measured in this work. The table quantifies the observations made from figure 2, and extends the discussion to even-even and odd-odd cases, and to low- and high-spin isomers in the same isotope.
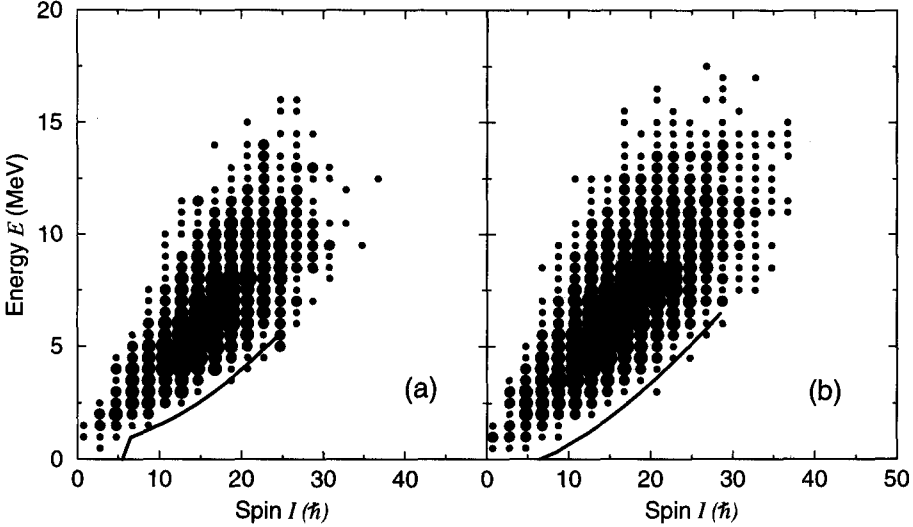

Figure 1. Preliminary two-dimensional (E, I) entry distributions for (a) ^{175}Au and (b) ^{175}Pt. The yrast line for each isotope is shown.
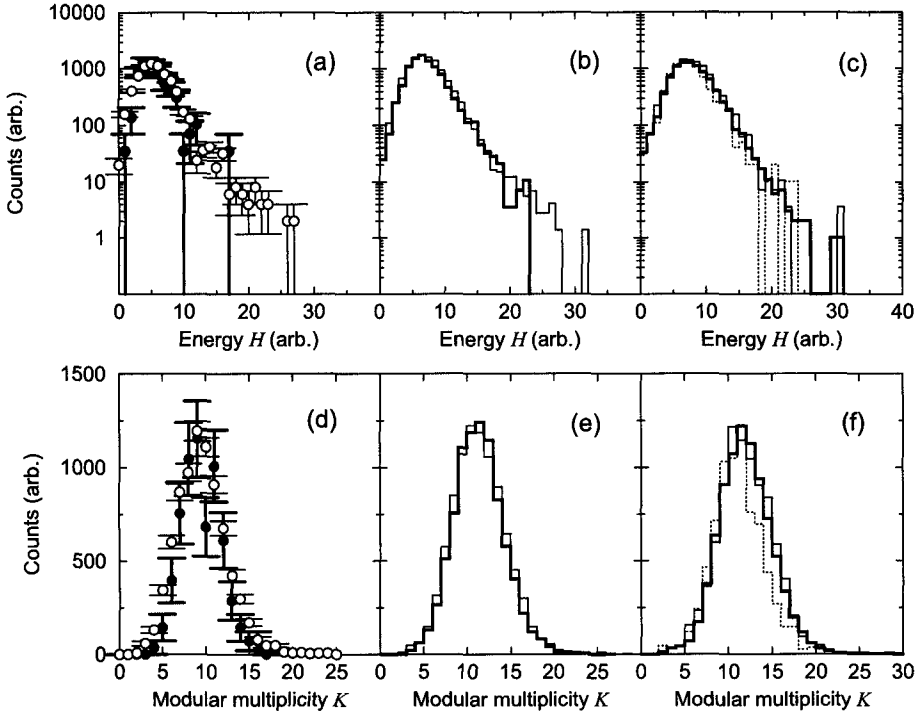
Figure 2. Normalised entry distributions for Au (thick line), Pt (thin line) and Hg (dotted line) isobars. The first three panels show modular energy distributions for (a) $A = 173$, (b) $A = 175$ and (c) $A = 177$. Panels (d), (e) and (f) show the analogous multiplicity distributions. Uncertainties are represented for the $A = 173$ data.

The H distributions for $A = 177$ isobars (figure 2(c)) are essentially identical, except for a possible more rapid fall-off at higher energies observed for ^{177}Hg. However, there is a clear distinction between the K distribution (figure 2(f)) of ^{177}Hg and those of its Pt and Au isobars. A difference of a full unit of multiplicity is observed in the average value quantified in table 1, and there is considerably less population of ^{177}Hg at higher spins. The lower multiplicity associated with ^{177}Hg is believed to be an effect caused by the strong competition from fission. Since most fission occurs at the time of compound-nucleus formation and is more important at higher angular momenta, we would naïvely expect multiplicity distributions to be the same for each of the $A = 177$ nuclei. However, fission also competes at each stage of the evaporation process and has its greatest effect for higher proton number Z. There is thus more fission, and therefore a lower multiplicity, in the population of the ^{177}Hg isobar, for which a simple estimate of the fissility, $Z^2/A = 36.2$, is comparable to that of ^{235}U and considerably greater than that of its Pt and Au isobars. Alternatively, the difference in the K distribution of ^{177}Hg (populated via the 3n

Table 1
Average modular energy, energy full-width half-maximum, average modular multiplicity and multiplicity full-width half-maximum associated with Pt, Au and Hg α-decays with $173 \leq A \leq 177$. The evaporation channel leading to each nucleus is provided. The uncertainty on the last digit is given in parentheses.

	$\bar{H}$	δH	$\bar{K}$	δK
^{173}Pt (2pn)	5.97(3)	5.0(5)	9 .42(5)	6.35(8)
^{174}Pt (2p2n)	5.69(3)	3.84(3)	10.02(8)	6.7(1)
^{175}Pt (2pn)	7.19(3)	5.34(3)	10.84(4)	7.05(6)
^{176}Pt (2p2n)	5.91(3)	4.75(3)	10.48(4)	7.13(6)
^{177}Pt (2pn)	7.78(3)	6.8(9)	11.42(6)	7.2(1)
^{173g}Au (p2n)	4.9(5)	5.5(3)	9.3(5)	5(1)
^{173m}Au (p2n)	5.9(2)	4.3(3)	9.4(2)	5.4(3)
^{174}Au (pn)	7.7(3)	5.6(2)	10.7(3)	5.8(6)
^{175}Au (p2n)	6.84(3)	5.25(3)	10.80(6)	6.6(1)
^{177g}Au (p2n)	7.69(9)	6.84(6)	11.57(9)	6.4(1)
^{177m}Au (p2n)	7.69(3)	5.44(3)	11.42(3)	6.90(6)
^{177}Hg (3n)	7.25(9)	5.88(6)	10.5(1)	6.5(2)

evaporation channel) compared to that of ^{177}Pt (2pn) and ^{177}Au (p2n) could be due to the larger binding energy of the neutron, compared to that of the proton, near to the proton dripline. However, such an effect should also be seen in comparing the K distributions of ^{177}Pt and ^{177}Au, which is not apparent in figure 2(f).

The maximum excitation energy in the proton-unbound ^{173,175}Au isotopes (figure 2(a,b)), produced via the p2n channel from ^{176,178}Hg compound systems, appears to be less than in the ^{173,175}Pt nuclei, populated following 2pn evaporation. It is not clear, however, that this effect is a real one, since the statistics for ^{173}Au are poor. The effect appears to be larger for the more proton-rich systems, and does not extend as far as $A = 177$ (figure 2(c)). We attribute the cut-off in excitation energy of the ^{173,175}Au isotopes to the weak binding of the last proton, relative to the stronger binding energy of the last proton in the Pt isobars. For the multiplicity projections in figure 2(d,e), the distributions for the Pt and Au isobars are essentially the same.

As summarised in table 1, the average energy and multiplicity for the odd-A Pt and Au nuclei decrease as a function of neutron number N. In both cases, the difference is greater between $A = 175$ and $A = 173$ than between $A = 177$ and $A = 175$, i.e. the effect is more pronounced when the final proton is less bound. For the even-even Pt isotopes the trend is the same, although it is difficult to draw a firm conclusion since only ^{174}Pt and ^{176}Pt have been measured. For the odd-odd Au nuclei, it has only been possible to determine an entry distribution associated with the stronger of the two ^{174}Au α-decays [12]; neither

of the decaying states have previous spin/parity or configuration assignments. The ^{174}Au distribution, which is statistically very poor, is similar to that of its isobar ^{174}Pt.

A comparison of the entry distributions associated with the ground state and excited state in ^{173}Au is difficult due to the low statistics associated with this reaction channel, in particular for population of the low-spin isomer. A comparison of two isomers in the same nucleus is possible, however, for the ^{177}Au isotope. In this case the energy and multiplicity leading to both states is almost identical. Although some differences may have been expected, the result is not surprising because of the nature of the high-spin ^{177}Au level scheme [9]. Virtually all of the yrast decay proceeds through one rotational sequence, and both decaying isomers are thus fed, essentially, by the same entry distribution.

4. CONCLUSION

In summary, we have measured entry distributions for several proton-rich isotopes of Pt, Au and Hg with $173 \leq A \leq 177$. Differences have been observed in both the energy and multiplicity distributions, particularly between proton-unbound Au systems and their more stable isobars. This is the first systematic study of such effects for nuclei near and beyond the proton dripline.

REFERENCES

1. P. Reiter *et al.*, Phys. Rev. Lett. 84 (2000) 3542.
2. C.N. Davids, B.B. Back, K. Bindra, D.J. Henderson, W. Kutschera, T. Lauritsen, Y. Nagame, P. Sugathan, A.V. Ramayya and W.B. Walters, Nucl. Instrum. Methods. Phys. Res. B 70 (1992) 358.
3. R.S. Simon, K.-H. Schmidt, F.P. Heßberger, S. Hlavac, M. Honusek, G. Münzenberg, H.-G. Clerc, U. Gollerthan and W. Schwab, Z. Phys. A 325 (1986) 197.
4. E.S. Paul *et al.*, Phys. Rev. C 51 (1995) 78.
5. I.Y. Lee, Nucl. Phys. A 520 (1990) 641c.
6. M. Jääskeläinen, Nucl. Instrum. Methods. Phys. Res. 204 (1983) 385.
7. Ph. Benet, Ph.D. thesis, L'Universitie Louis Pasteur de Strasbourg, CRN/PN 88-29, 1988.
8. T. Lauritsen *et al.*, Phys. Rev. Lett. 69 (1992) 2479.
9. F.G. Kondev *et al.*, contribution to these proceedings and to be published.
10. G.L. Poli *et al.*, Phys. Rev. C 59 (1999) R2979.
11. F.G. Kondev *et al.*, to be published.
12. R.D. Page, P.J. Woods, R.A. Cunningham, T. Davinson, N.J. Davis, A.N. James, K. Livingston, P.J. Sellin and A.C. Shotter, Phys. Rev. C 53 (1996) 660.